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On the interpretation of high-energy neutrino limits

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Abstract: Recent results from the AMANDA experiment yield limits on the extraterrestrial neutrino flux, based on different analysis methods. A limit on the diffuse neutrino flux is derived at high energies, i.e. between $10^{4.2}$ GeV and $10^{6.4}$ GeV. The stacking of different AGN subclasses gives a point source limits for each of the classes. In this contribution, a method of interpreting stacking point source limits as diffuse limits to the particular source classes is presented. While 11 source classes are used for AMANDA's current stacking analysis, further source catalogs suitable for an analysis are discussed. The catalogs are investigated with respect to the sources' distribution in the sky. In particular, the capabilities of IceCube and KM3NeT, are examined. Since these second generation detectors are going to have complementary fields of view (FoV), the fraction of the signal in the IceCube's and KM3NeT's FoV ($\sim$ northern resp. southern hemisphere) is discussed.

Introduction

The prediction that a flux of high-energy neutrinos, $E_\nu > 100$ GeV, is present from extragalactic sources derives from the fact that high-energy Cosmic Rays and photons have been observed. Protons can interact with photon fields or other protons in the source or during propagation to produce a Delta-resonance. The latter decays to produce charged and neutral pions which in turn leads to the production of neutrinos from charged pion decays and high-energy photons from neutral pion decays. The decay chain for proton photon interactions looks as follows:

$$
\begin{aligned}
p\,\gamma &\rightarrow \Delta^+ \\
\Delta^+ &\rightarrow \begin{cases} p\,\pi^0 \rightarrow (p)\gamma\gamma \\ n\,\pi^+ \rightarrow (n)\mu^+\,\nu_\mu \rightarrow e^+\,\nu_e\,\overline{\nu}_\mu\,(\nu_\mu) \end{cases}
\end{aligned}
$$

The photons from the π^0-decay originate at TeV energies in optically thin sources, while they cascade down to keV-GeV energies in optically thick sources. Therefore, the main criterion for the selection of neutrino sources is their strength in high-energy photons. The most luminous photon sources are expected to be the brightest sources in neutrinos as well. In this paper, possible sources of neutrino emission will be examined with respect to the most restrictive neutrino flux limits given by the AMANDA experiment.

Neutrino flux limits

At the highest energies, experiments for the detection of neutrinos have to deal with a large background from atmospheric neutrinos. Different strategies are used to reduce this background. The search for a diffuse contribution is performed by looking for an excess of neutrinos at the highest energies, i. e. $E_\nu > 10$ TeV. Extragalactic neutrino spectra are typically about one to two powers harder than the atmospheric contribution. Another possibility is to search for individual point sources. Such a point source search can be optimized by not only looking at single sources, but at the most luminous objects of a certain class. This method is referred to as the *stacking approach* and has been performed for 11 classes of Active Galactic Nuclei (AGN) as described in [1]. In each of the cases, upper limits to the extraterrestrial neutrino flux could be derived. The limit to the diffuse flux will be labeled Φ^{DL}, with the units GeV cm^{-2} s^{-1} sr^{-1}. The most stringent limit is given in [2] as

$$\Phi^{\mathrm{DL}} = 7.4 \cdot 10^{-8} \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}\,. \qquad (1)$$

The stacking limits to a certain source class will be referred to as Φ^{SL} with the units GeV cm^{-2} s^{-1} in the following. In order to compare the stacking results with a diffuse contribution from the investigated source class, the stacking limit has to be converted into a stacking diffuse limit by taking into account the contribution from weak sources:

$$\Phi^{\mathrm{SDL}} = \frac{\epsilon \cdot \xi}{2\,\pi\,sr} \cdot \Phi^{\mathrm{SL}}\,. \qquad (2)$$

Here, ϵ is the *stacking factor*, considering weak, identified sources which were not included in the stacking analysis. The second factor ξ is referred to as the *diffusive factor*, taking into account sources which have not been resolved by photon experiments, since they are too weak, but which contribute to a diffuse flux. The two factors are explained in more detail is [3]. While the stacking factor can be estimated very well, since the factor is based on observations, the diffusive factor is unknown especially for source classes with a high source density at low luminosities. The contribution from unresolved sources can become quite high, but it is often unknown due to insufficient sensitivities (see e.g. the case of FR-I and FR-II galaxies). In the case of EGRET-detected sources, on the other hand, it is relatively well-known, since EGRET measured the diffuse GeV component, and a factor of $\xi_{EGRET} \leq 12$ is given [4].

Stacking diffuse limits

The resulting neutrino flux limits from the stacking limits are given in Table 1. In some cases, the diffusive factor ξ is difficult to estimate as discussed above. Therefore, it has been left as a free parameter in the table. For EGRET identified and unidentified sources, the general diffuse limit and the stacking diffuse limit are comparable. The main advantage of the stacking method lies in the lower energy threshold. Figure 1 shows the neutrino energy spectrum associated with the diffuse background as measured by EGRET. While the diffuse limit ranges from $10^{4.2}$ GeV up to $10^{6.4}$ GeV, the stacking diffuse limit restricts neutrino flux models between 10^3 GeV up to 10^6 GeV. Thus, the two limits are complementary. At the lowest energies, the neutrino flux from proton proton interactions can be tested with IceCube using the stacking method, while proton photon interactions are easy to test with a diffuse search at higher energies [5, 6].

Source class	Φ^{SL}	Φ^{SDL}	$\Phi^{\mathrm{DL}}/\Phi^{\mathrm{SDL}}$
EGRET GeV	2.71	7.25	1.02
unid. EGRET	31.7	6.56	1.23
keV (ROSAT)	9.71	2.65	2.79
CSS/GPS	5.94	$1.23 \cdot \xi$	$6.02/\xi$
FR-I w/o M-87	2.91	$0.51 \cdot \xi$	$14.5/\xi$
FR-II	30.4	$2.05 \cdot 10^3$	$3.61 \cdot 10^{-3}$
QSOs	6.70	$1.39 \cdot \xi$	$5.34/\xi$

Table 1: Source classes with stacking limits from [1]. Stacking diffuse limits have been calculated as described in the first section. They are compared to the general diffuse limit from [2].

Source classes: north vs. south

While IceCube is only sensitive to the northern hemisphere in the muon-neutrino channel, KM3NeT will mostly be sensitive to the southern hemisphere. Therefore, it is interesting to compare the distribution of sources in the sky with respect to the two hemispheres. In this section, we will first consider those catalogs having been analyzed with AMANDA data already in order to investigate source class capabilities of the northern and southern hemispheres. In a second part, additional source classes are proposed for investigation.

EGRET and FR-I galaxies

In the case of already analyzed source classes, we focus on FR-I galaxies and EGRET sources as examples. For the investigation of all eleven classes see [3]. Figure 2 shows the total flux in the sample of FR-I galaxies as a function of the number of included sources. We start with the strongest source, then add the second strongest and so forth, until all resolved objects are considered. Triangles

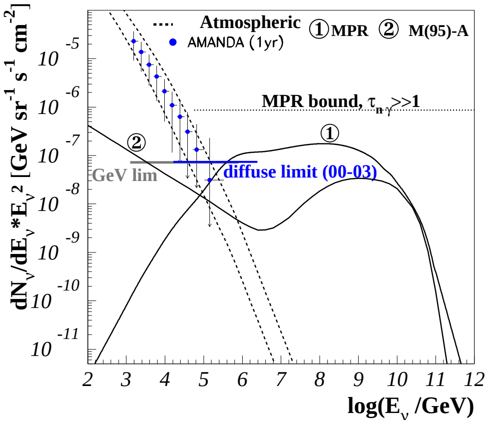

Figure 1: Neutrino flux predictions for optically thick sources, normalized to the diffuse EGRET flux above 100 MeV. Model 1 (*MPR*) is given in [6], model 2 (*M(95)-A*) is calculated in [5]. The stacking diffuse limit for the class of identified EGRETsources is indicated with $\xi = \xi_{\max} = 12$ where it is assumed that AGN produce the complete diffuse EGRET signal. The dashed lines represent the atmospheric background [7] and blue data points are from AMANDA-II [8].

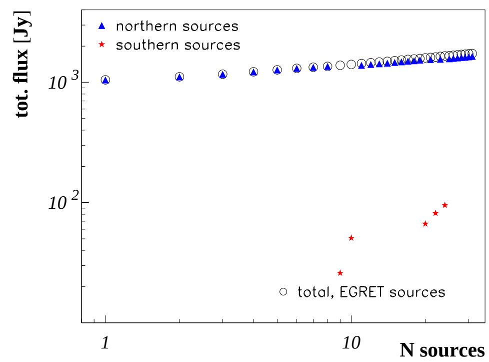

Figure 2: The total flux as a function of the number of included sources for FR-I galaxies. Triangles: northern sources; stars: southern sources; circles: complete catalog.

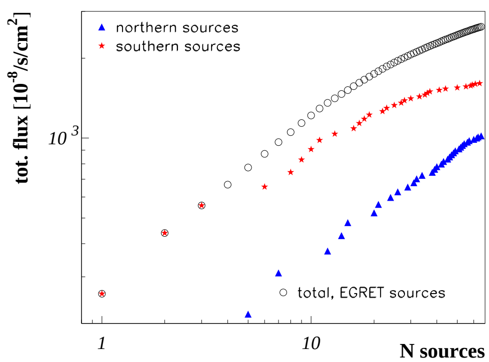

Figure 3: The total flux as a function of the number of included sources for FR-I galaxies. Triangles: northern sources; stars: southern sources; circles: complete catalog.

indicate the summation of northern sources, while stars represent southern sources only. Circles show the complete catalog. The main signal in this case comes from the northern hemisphere, since only a few sources are identified in the south. The main reason here is a selection effect, since the northern sky has been studied in more detail. GeV emission from AGN could be studied equally for both hemispheres by the EGRET experiment on board of the CGRO satellite. Here, the three most luminous sources are in the southern sky as it can be seen in Fig. 3. A stacking analysis as it was performed with AMANDA could be improved by a high-energy neutrino telescope like KM3NeT located in the Mediterranean. While only 67 AGN could be identified with EGRET, the GLAST experiment will presumably provide a more detailed study of GeV emission from AGN together with a precise measurement of the diffuse component.

Study of additional source classes

In addition to the catalogs already investigated with AMANDA, the following catalogs can be interesting to study in the context of neutrino emission: MeV emission from AGN has been proposed to originate from π^0- decays, implying the coincident production of neutrinos [5]. This makes it interesting to investigate COMPTEL sources [9], with the disadvantage that only 11 AGN are identified at energies of $<$ 100 MeV. INTEGRAL on the other hand is sensitive to soft gamma-rays with a total of 42 identified sources [10]. These sources can be connected to neutrino emission as well, as it is done in [5]. A study of *INTEGRAL* hard X-ray sources [10] can improve the previous analysis done with HEAO-A data. This way, the general diffuse limit can be tested, which indicates that X-ray emission from AGN is *not* correlated to neutrino emission. *Starburst* galaxies have been suggested as emitters of high-energy neutrinos [11]. The model should be considered as an upper limit to the flux. It is presumable at least about a factor of five lower than predicted in [11], since not all of the FIR background comes from starbursts as pointed out in [12].

A summary of the distribution of sources in the sky with respect to the southern and northern hemisphere is given in Table 2. For each of the four catalogs, the number of sources in the southern and northern sky is given as well as the fraction of signal S in the two hemispheres. Here, S_{tot} indicates the total flux in a sample, S_{south} and S_{north} give the total flux in the southern resp. northern hemisphere. While the signal from COMPTEL and INTEGRAL soft gamma-ray sources are relatively uniformly distributed, most of the signal from INTEGRAL hard X-ray sources comes from the southern hemisphere (74%). A catalog of 199 starburst galaxies has most sources in the supergalactic plane and therefore, 87% of the signal comes from the northern hemisphere.

Catalog	#south/#north	$\frac{S_{tot}^{south}}{S_{tot}}$	$\frac{S_{tot}^{north}}{S_{tot}}$
COMPTEL [9]	5/6	0.51	0.49
INTEGRAL [10] (hard X-rays)	10/5	0.74	0.26
INTEGRAL [10] (soft γ rays)	23/19	0.60	0.40
Starbursts	46/153	0.13	0.87

Table 2: Summary of the main parameters in the proposed source catalogs for neutrino observation. The number of sources in the southern and northern hemisphere are listed as well as the fraction of signal in the southern resp. northern hemisphere.

Conclusions & Outlook

In this contribution, we present a method to interpret stacking limits as diffuse limits. This works well for source classes with only small contributions from distant, faint sources, as it is the case for EGRET sources. In the case of a large population of weak sources as in the case of FR-I galaxies, the general diffuse limit is typically more restrictive. Stacking diffuse limits give restrictions to the isotropic neutrino flux from the investigated source class. The method is sensitive down to $\sim$ 1 TeV and therefore complementary to the diffuse search where high-energy events ($E_\nu > 10$ TeV) are analyzed. The limits discussed above are derived using sources in the northern hemisphere. In this paper, we compare the source class capabilities of the southern and northern hemisphere. It can be shown that for several source catalogs, the signal is mainly focused in the northern hemisphere (e.g. FR-I galaxies) which makes an analysis with IceCube very effective. Other classes such as EGRET sources have the dominant contribution in the southern hemisphere. An analysis of these sources will most likely be more effective with an instrument located in the Mediterranean.

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